Neutrino production in UHECR proton interactions in the infrared background

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We discuss the contribution of proton photoproduction interactions on the isotropic infrared/optical background to the cosmic neutrino fluxes. This contribution has a strong dependence on the proton injection energy spectrum, and is essential at high redshifts. It is thus closely correlated with the cosmological evolution of the ultra high energy proton sources and of the inrared background itself. These interactions may also contribute to the source fluxes of neutrinos if the proton sources are located in regious of high infrared emission and magnetic fields.

The assumption that the Ultra High Energy Cosmic Rays (UHECR) are nuclei (presumably protons) accelerated in luminous extragalactic sources provides a natural connection between these particles and ultra high energy neutrinos. This was first realized by Berezinsky&Zatsepin [1] soon after the introduction of the GZK effect [2]. The first realistic calculation of the generated neutrino flux was made by Stecker [3]. The problem has been revisited many times after the paper of Hill&Schramm [4] who used the non-detection of such neutrinos to limit the cosmological evolution of the sources of UHECR.

These so called cosmological neutrinos are produced in photoproduction interactions of the UHECR with the ambient photon fields, mostly with the microwave background radiation (MBR). The GZK effect is the limit on the highest energy a cosmic ray proton can retain in propagation through the MBR. It sets a cutoff in the cosmic ray energy spectrum in case the UHECR sources are isotropically and homogeneously distributed in the Universe. The physics of these photoproduction interactions is very well known. Although the energy of the interacting protons is very high, the center of mass energy is low, mostly at the photoproduction threshold. The interaction cross section is studied at accelerators and is very well known. Most of the interactions happen at the Δ^+ resonance where the cross section reaches 500μb. The mean free path reaches a minimum of 3.4 megaparsecs (Mpc) at proton energy of 6×10^{20} eV. The average energy loss of 10^{20} protons is about 20% per interaction and slowly increases with the proton (and center of mass) energy.

The fluxes of cosmological neutrinos are, however, very uncertain because of the lack of certainty in the astrophysical input. The main parameters that define the magnitude and the spectral shape of the cosmological neutrino fluxes are: the total UHECR source luminosity L_{CR}, the shape of the UHECR injection spectrum α_{CR} in the case of power law spectrum, the maximum UHECR energy at acceleration E_{max} and the cosmological evolution of the UHECR sources. These are the same parameters that Waxman&Bahcall [5] used to set a limit on the neutrino fluxes generated in optically thin sources of UHECR.

The microwave background is not the only universal photon field that has to be taken in consideration. Especially interesting is the isotropic infrared and optical background (IRB). The number density of IRB is smaller than that of MBR by more that two orders of magnitude. On the other hand, protons of lower energy can interact on the IRB, and the smaller number density has to be weighted with the larger flux of interacting protons. The present Universe is optically thin to 10^{19} eV and lower energy protons, but even at small redshift the proton interaction rate quickly

increases. This is different from the interactions on MBR, where the interacting protons quickly lose their energy even at z=0. The cosmological evolution of UHECR injection is thus of major importance for the contribution of such interactions to the flux of cosmological neutrinos.

We use the IRB model of Franceschini et al [6] shown in Fig. 1 together with the MBR in terms of energy density. The model consists of two components: 'star', near infrared, which covers the higher photon energies, and 'dust', far infrared that continues down to MBR. The total IRB number density is significantly smaller than that of MBR. The model yields 1.6 photons/cm^3, a factor of 250 less than the MBR. The IRB is measured directly after subtraction of point sources and is also estimated from the absorption of TeV photons coming from extragalactic sources [7]. These estimates affect mostly the near infrared part of the spectrum. Photons of wavelength above 40 μm affect only the γ-ray fluxes above 10 TeV [8] where the statistics is usually low and the flux decrease could also be due to absorption in the γ-ray sources.

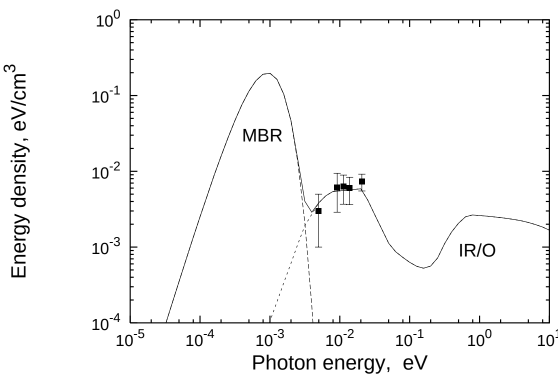

Figure 1. The energy density in MBR and IRB according to the model of Ref. [6]. The data points are from analyses of the DIRBE measurements [9,10].

In addition to the lower total photon density the IRB covers much wider wavelength range than the microwave background, and its photon density per unit energy is even smaller. The interactions of UHECR on IRB photons are indeed very rare in the present universe. Fig. 2 shows the fraction of the proton energy that is converted to neutrinos as a function of the proton energy in propagation on a distance of 200 Mpc.

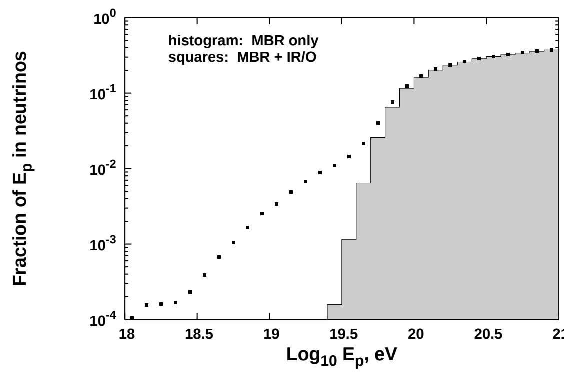

Figure 2. Fraction of the proton energy that is converted to neutrinos on propagation on 200 Mpc. The histogram shows interaction on MBR only, while the points represent interactions of the photon spectrum shown in Fig. 1.

In the derivation of the neutrino limit Waxman&Bahcall use cosmic ray source luminosity $L_{CR} = 4.5 \pm 1.5 \times 10^{44}$ erg/Mpc^3/yr between 10^{19} and 10^{21} eV for power law cosmic ray energy spectrum with $\alpha = 2$. The assumption is that no cosmic rays are accelerated above 10^{21} eV. The cosmological evolution of the source luminosity is assumed to be $(1+z)^3$ to $z = 1.9$ then flat to z=2.7 with an exponential decay at larger redshifts. We will first use the parameters of this limit to find the contribution of the proton interactions on IRB.

The resulting $\nu_\mu + \bar{\nu}_\mu$ spectrum for a cosmological model with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and H_0 = 75 km/s/Mpc is shown with a dotted line in Fig. 3. The flux peaks at $10^{16.3}$ eV at 2.5×10^{-18} cm^{-2}s^{-1}ster^{-1}. The peak is at energy lower than

the peak of the MBR interactions (shown with a dash-dot line) by a factor of 20, and its magnitude is also lower by a factor of 10. Next we show in the same figure with a dashed line the contribution of IRB for a scenario in which the injection spectral index is changed to $\alpha = 2.5$ and all other parameters are the same. There is a noticeable shift of the peak position to still lower energy. The peak is now located at $10^{15.7}$ eV and is higher by a factor of about 7. The contribution of IRB is now smaller than that of MBR ($\alpha = 2$) only by about 30%. The highest curve in Fig. 3 shows the IRB contribution for $\alpha = 2.5$ and cosmological evolution with $n = 4$ and then constant to z=10 followed by an exponential decrease. The location of the peak does not change but its magnitude increases by almost a factor of three. It is now 50% higher than the 'standard' MBR generated cosmological neutrinos. It is obviously not correct to compare fluxes obtained with different assumptions for the cosmological evolution and we do it only to have a feeling for the magnitude of the neutrino fluxes. The $\alpha = 2.5$ spectra decrease the flux of cosmological neutrinos of energy above 10^{19} eV.

Both the spectral shape and the cosmological evolution of the UHECR sources affect the contribution of the IRB to the cosmological neutrino flux. The most important factor, however, is the shape of the injection spectrum. It is worth to note that the maximum proton energy at acceleration does not affect the IRB generated fluxes, since they are due mostly to protons of energy below 10^{20} eV, as can be observed in Fig. 2

At energy about 3×10^{18} eV the cosmological fluxes of $\nu_\mu + \bar{\nu}_\mu$ are very close to the limit for source neutrinos. The reason is simple - in propagation from large distances protons lose almost all of their energy in interactions on MBR. An interesting feature is the flux of $\bar{\nu}_e$ (not shown), which peaks at energy about 3×10^{15} eV. The origin of this flux is neutron decay, and a small $\bar{\nu}_e$ flux is generated in neutron interactions on MBR.

The cosmological evolution of the sources (n=3) increases the fluxes by about a factor of five compared to a no-evolution scenario. The increase, however, is not energy independent [12]. The highest energy neutrinos are generated at

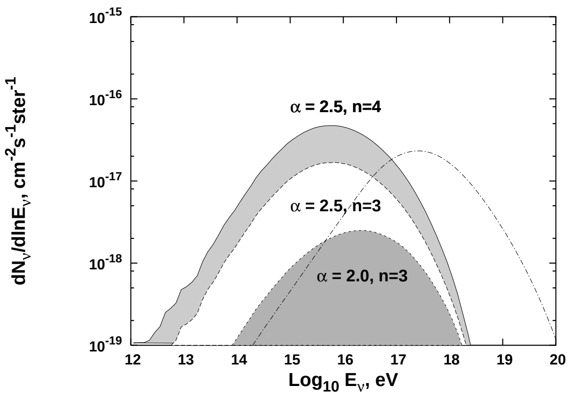

Figure 3. Fluxes of cosmological neutrinos ($\nu_\mu + \bar{\nu}_\mu$) generated only by interactions on IRB. All three calculations use the UHECR luminosity derived by Waxman [11]. The power law spectral indices and the cosmological evolution of UHECR sources n are given by each curve. The dash-dotted line shows the 'standard' n=3 cosmological neutrino flux from interactions in the MBR.

small redshifts. The low energy neutrinos come from high redshifts because of two reasons: the threshold energy of protons for photoproduction interaction decreases, and the generated neutrinos are further redshifted to the current epoch. The standard flux (α=2.0, n=3) would generate about 0.4 neutrino induced showers per km^3 year in the IceCube [14] neutrino detector and 0.9 events with energy above 10^{19} eV in the Auger[15] observatory (for target mass of 30 km^3 of water) assuming that at arrival at Earth the flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ is 1:1:1 because of neutrino oscillations. It is difficult to estimate the rate in EUSO [16] because of its yet unknown energy threshold. These events come from the NC interactions of all neutrinos, CC interactions of ν_e, the hadronic (y) part of the CC interactions of muon and tau neutrinos and from τ decay. Although very prominent, the Glashow resonance does not produce high rate of events because of its narrow width. Ice Cube should also detect very energetic muons with a comparable rate which is difficult

to predict without detector Monte Carlo simulations.

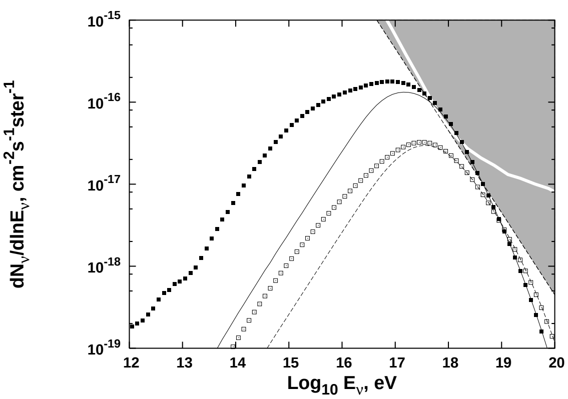

Figure 4. Comparison of the cosmological neutrino fluxes with the Waxman&Bahcall limit, which is given as an shaded area for the 'standard' power law injection spectrum and cosmological evolution. The thick white line shows the limit derived in Ref. [13]. The dashed line shows the flux of cosmological neutrinos generated in interactions on MBR for the 'standard' parameters, and the solid one - for $\alpha = 2.5$ and $n = 4$. The squares show the fluxes generated on the total photon background shown in Fig. 1: the open squares are for the 'standard' parameters and the full ones - for $\alpha = 2.5$ and $n = 4$.

Changing the proton injection spectrum to a power law with $\alpha = 2.5$ moves the maximum of the cosmological neutrino flux to lower energy and increases the contribution of the interactions on IRB. At the same time the flux of higher energy cosmological neutrinos decreases. The shower event rates in IceCube and Auger become 0.44 and 0.31 respectively.

Assuming a stronger source evolution, $(1 + z)^4$ makes a big difference in the expected fluxes. With a power law source spectrum with $\alpha = 2.5$ it generates 1.2 events in IceCube and 0.66 events in Auger. The cosmological neutrino spectrum for $\nu_\mu + \bar{\nu}_\mu$ is shown with full squares in Fig. 4. The contribution of interactions on MBR is shown with a solid line.

The biggest uncertainty in these results, which is not listed above, is the cosmological evolution of the infrared/optical background. The estimates above assume that it is the same as of MBR, i.e. that the IRB was fully developed at z=8, which is the limit of the redshift integration. This does not seem to be a realistic assumption, although models of the IRB emission [17] predict very strong evolution of the far infrared emission, especially between redshifts of 10 to 100.

The maximum proton energy at acceleration E_{max} is unknown, but having in mind the highest energy Fly's Eye shower of 3×10^{20} eV one should expect that astrophysical sources accelerate protons at least to 10^{21} eV. The injection spectrum is also not very well determined since the result of proton propagation depends on the UHECR source distribution. Attempts to derive the injection spectrum in the case of isotropic homogeneous source distribution end up with injection spectra not flatter than $E^{-2.4}$ power law [18,19]. . The extreme case is developed by Berezinsky et al. [20] who derive an α=2.7 injection spectrum.

The luminosity required for the explanation of the observed events above 10^{19} eV grows with the spectral index, and in the case of Berezinsky et al. becomes 4.5×10^{47} erg Mpc^{-3}yr^{-1}. Such steep spectrum would generate only a small event rate for neutrinos above 10^{19} eV and would enhance the IRB contribution.

Expressed in terms of $(1 + z)^n$ the cosmological evolution of different astrophysical objects is observed to be between $n = 3$ and 4. A strong evolution with $n = 4$, as used above, may be too optimistic, but not entirely out of range. As seen from Fig. 4 strong cosmological evolution does not only increase the total flux, but moves the peak of the cosmological neutrino spectrum to somewhat lower energy.

Finally, the cosmic ray source luminosity, which was normalized to the flux of UHECR at 10^{19} by Waxman [11] could easily be higher or lower by half an order of magnitude. One can then assume a pessimistic IceCube shower event rate of 0.1 event per km^{3}yr and an optimistic rate of 4-5 events.

It is obvious that a detailed calculation of the flux of cosmological neutrinos should include the interactions on the infrared background. We plan to do that with a better model of the IRB cosmological evolution and describe the calculation in more detail in a forthcoming paper. One should also keep in mind that if the UHECR sources are located in regions of high infrared and optical photon density, the fluxes of source neutrinos could increase. The effect may be much stronger if 10^{19} eV and lower energy protons are contained in the region by high magnetic fields.

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